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Modeling thermally activated domain wall dynamics in thin magnetic strips with disorder

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Abstract. We study the effect of disorder and temperature on the field-driven dynamics of a transverse domain wall occurring in thin and narrow magnetic strips made of a soft magnetic material such as permalloy. Motivated by a micromagnetic description of such a domain wall, we construct a model based on two coupled flexible lines enclosing the domain wall transition region, capturing both the finite width and the characteristic V-shape of the wall. Disorder is included via randomly distributed pinning centers interacting with the two lines. We study the field-driven dynamics of the domain wall in disordered strips in a finite temperature, and compare our findings to experimental observations of stochastic domain wall dynamics.

1. Introduction

Future forms of memory and logic devices are likely to involve devices such as the racetrack memory [1] and other applications [2, 3, 4] where the local magnetization of narrow and thin magnetic nanostrips or wires is used to store or process information. Such devices rely on the ability to displace the magnetic domain walls in a controlled fashion, by applying field or current pulses. In practice, any material from which such wires and strips are made of will include various sources of disorder, such as roughness of the edges and surfaces of the sample, as well as various point-like impurities present in the bulk of the wire/strip. Such disorder, together with thermal effects, will affect the domain wall dynamics, especially for low driving fields. Thus, understanding and controlling the effect of such imperfections presents a challenge with possible implications also for various practical applications of domain wall dynamics in wires or strips. Previous studies addressing the effect of disorder in nanostrips have focused on the effect of edge roughness [5, 6, 7] and notches [8]. However, the majority of theoretical studies of domain wall dynamics in such systems has been considering “perfect” systems, free of any imperfections which in practice are always present in any realistic sample.

In this paper we present a simplified model of the so-called transverse domain wall occurring in thin and narrow nanostrips made of a soft magnetic material such as permalloy [9], taking into account “bulk” imperfections. The model is based on two flexible lines enclosing the transition region of the domain wall and provides a useful intermediate description between full micromagnetic modeling and the so-called *1d* models in which the domain wall is reduced into a *1d* magnetization profile [10]. In particular, the model captures the finite width and

the characteristic shape of the domain wall resembling a letter V [11]. Disorder describing e.g. thickness fluctuations of the strip can also be included in a natural way, as randomly distributed pinning centers interacting with the two lines. The paper is organized as follows: In the following Section, the line-based model is presented, while in Section 3, some preliminary numerical results will be presented and compared qualitatively to experimental observations. In Section 4 we present our conclusions.

2. The line-based model

We consider here a strip of length L , width W and thickness D , satisfying $L \gg W \gg D$, made of a soft magnetic material such as permalloy. As the anisotropy energy in soft magnetic materials is dominated by shape anisotropy, the domains lie along the long axis of the strip. We focus here on the case where W and D are sufficiently small such that the stable domain wall structure is the so-called transverse wall [9].

Due to the balance between exchange and magnetostatic interactions, the equilibrium shape of the transverse domain wall resembles the letter V. Here we consider a simplified description of such a wall structure by taking the wall to be composed of two coupled flexible lines enclosing the transition region of the domain wall (see Fig. 1). Within this approximation the magnetic charges of the transverse wall are taken to be concentrated along these two lines (with the charge density depending on the local orientation of the line) and at the strip edges. These charges give rise to demagnetizing fields \vec{H}_{dm} acting on the segments of the two lines. Further ingredients of the model include line tension γ_w of the lines, representing the energy cost due to deformations of the wall, as well as a repulsive interaction between the two lines, both originating from the exchange interactions.

2.1. The 1d model

As our model is a generalization of the so-called 1d model for a 180° domain wall in a wire, we will first briefly review its main features [10]. The magnetization profile $\vec{m}(x)$ along the wire (x axis) is described by the polar and azimuthal angles θ and ϕ via the ansatz

$$\theta(x, t) = 2 \tan^{-1} \exp \left(\frac{x - q(t)}{\Delta(t)} \right), \quad (1)$$

$$\phi(x, t) = \phi(t), \quad (2)$$

where $q(t)$, $\Delta(t)$ and $\phi(t)$ are the domain wall position, width and (out-of-plane) magnetization angle, respectively. By expressing the various micromagnetic energy contributions (such as exchange, anisotropy and applied field) in terms of these *collective coordinates*, one can derive from a Lagrangian formulation the equations of motion, or the *Slonczewski equations*, for $q(t)$, $\phi(t)$ and $\Delta(t)$ [10]:

$$\alpha \frac{\dot{q}}{\Delta} + \dot{\phi} = \gamma_0 H_a, \quad (3)$$

$$\frac{\dot{q}}{\Delta} - \alpha \dot{\phi} = \gamma_0 H_K \frac{\sin 2\phi}{2}, \quad (4)$$

$$\dot{\Delta} = \frac{\gamma_0}{\alpha \mu_0 M_s a} \left[\frac{A}{\Delta} - (K_0 + K \sin^2 \phi) \Delta \right]. \quad (5)$$

Here, α is the damping coefficient, γ_0 is the gyromagnetic ratio, H_a is the applied field, K_0 and K are anisotropy constants, H_K is the anisotropy field corresponding to K (i.e. anisotropy perpendicular to the plane), μ_0 is the vacuum permeability, M_s is the saturation magnetization, $a = \pi^2/12$, and A is the exchange constant.

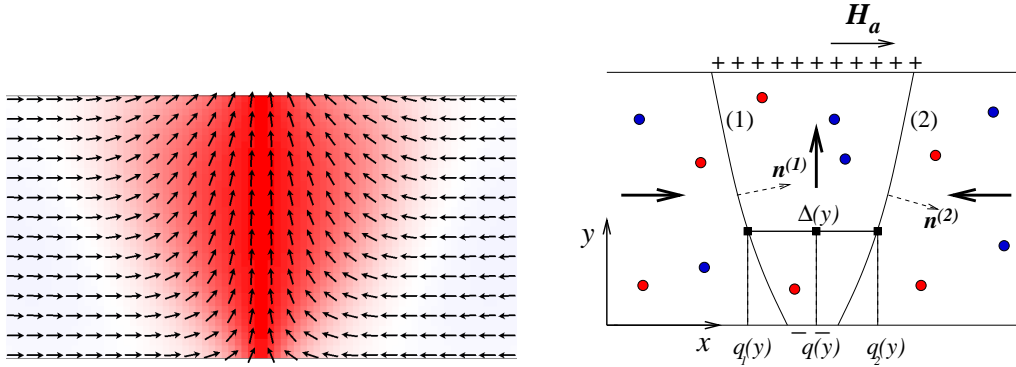


Figure 1. Left: The micromagnetic structure of the transverse domain wall. Right: A schematic of the line-based model, with the two coupled lines (1) and (2) enclosing the domain wall transition region. The model consists of a set of coupled “1d models”, with y -dependent widths $\Delta(y)$ and positions $q(y)$, related to the coordinates of the lines $q_1(y)$ and $q_2(y)$ via Eq. (7). Disorder is included via pinning sites which either attract or repel (blue and red dots, respectively) the domain wall.

2.2. Equations of motion for the line-based model

The line-based model is essentially a 2d generalization of the 1d model. The magnetization is described by the angles $\theta(x, y, t)$ and $\phi(t)$, with the former given by the 2d ansatz

$$\theta(x, y, t) = 2 \tan^{-1} \exp \left(\frac{x - q(y, t)}{\Delta(y, t)} \right), \quad (6)$$

where the domain wall position $q(y, t)$ and width $\Delta(y, t)$ now depend on the transverse coordinate y . Thus, the domain wall is modeled essentially as a set of 1d profiles, with y -dependent positions and widths. The coordinates $q(y, t)$ are related to the coordinates $q_1(y, t)$ and $q_2(y, t)$ of the two lines enclosing the domain wall transition region via

$$q_1(y, t) = q(y, t) - \frac{\Delta(y, t)}{2}, \quad q_2(y, t) = q(y, t) + \frac{\Delta(y, t)}{2}. \quad (7)$$

By employing a similar procedure as in the case of the 1d model, one obtains the equations of motion for the coordinates of the two lines,

$$\dot{q}_1 = \frac{\Delta}{\alpha} (\gamma_0 H_a - \dot{\phi}) - \frac{\gamma_0}{2\alpha\mu_0 M_s a} \left[\frac{A}{\Delta} - \Delta K \sin^2 \phi \right], \quad (8)$$

$$\dot{q}_2 = \frac{\Delta}{\alpha} (\gamma_0 H_a - \dot{\phi}) + \frac{\gamma_0}{2\alpha\mu_0 M_s a} \left[\frac{A}{\Delta} - \Delta K \sin^2 \phi \right], \quad (9)$$

$$\dot{\phi} = \frac{\gamma_0}{1 + \alpha^2} H_a - \frac{\gamma_0 \alpha}{2(1 + \alpha)} H_K \sin 2\phi. \quad (10)$$

In addition, the exchange energy in the y direction leads to an effective line tension which, together with the long-range magnetostatic interactions, couples the different “1d models”. The latter are taken into account by approximating the distribution of magnetic charges in the domain wall by concentrating them on the two lines (as if they would represent two 90° domain walls) and along the strip edges, see Fig. 1. These charges then give rise to magnetostatic fields acting on the segments of the two lines similarly to the applied field. Disorder is modeled via randomly distributed pinning centers which exert either an attractive or repulsive force on the

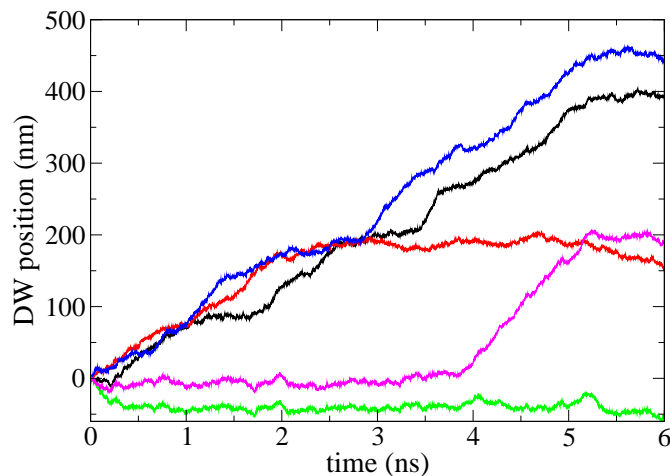


Figure 2. The domain wall position as a function of time due to a 5 ns field pulse starting at $t = 0$. Five different simulation runs with the same parameters but with different realizations of the disorder.

domain wall, representing for instance thickness fluctuations of the strip. In addition, we add a Gaussian white noise term representing the effect of temperature acting on the segments of the two lines. Here we restrict ourselves to consider the field-driven dynamics, but extending the model to include the effect of a spin-polarized electric current is straightforward. Also, only fields well below the Walker field H_W [12] are considered, as the model does not capture the domain wall magnetization reversal taking place for $H_a > H_W$ in the strip geometry via nucleation and propagation of an antivortex [10].

3. Numerical simulations

We investigate the thermally activated creep motion of the transverse wall by integrating numerically the equations of motion (8-10). We use material parameters of a soft magnetic material such as permalloy, i.e. $\alpha = 0.01$, $A = 1.5 \cdot 10^{-11}$ J/m, and $M_s = 8.0 \cdot 10^5$ A/m. To study the effect of disorder and temperature on the domain wall dynamics, we apply a field pulse of 5 ns duration, and monitor the induced displacement of the domain wall. Fig. 2 shows the domain wall position from five simulation runs with different realizations of the disorder with the same parameters. See also the attached video clip of an example simulation run. The domain wall dynamics in this low field regime is clearly stochastic, with a broad distribution of domain wall displacements: sometimes the domain wall does not move at all during the applied field pulse, while some other runs lead to significant displacements of hundreds of nanometers. This is a typical feature of thermally activated subthreshold creep motion: The domain wall spends a significant fraction of the time pinned by the disorder, and occasionally jumps forward due to thermal activation. Such motion is inherently stochastic, and naturally leads to a broad distribution of the domain wall displacements/velocities. Similar stochastic and broadly distributed domain wall velocities have been observed also in experiments [13].

4. Conclusions

Our model serves as a useful intermediate description between full micromagnetic simulations and the 1d models, capturing for instance the realistic V-shape of the transverse wall. The present version of the model also has the advantage that realistic physical units and parameters can be used in a transparent way [11]. Also, it is particularly suitable for studies of the effect of disorder on the domain wall dynamics.

Numerical simulations of the model in the low field regime reveal stochastic creep motion of the domain wall, leading to a broad distribution of domain wall displacements/velocities. Such stochastic dynamics is also in qualitative agreement with some recent experimental observations [13]. Future challenges include to understand in more detail the effect of various sources of disorder and thermal fluctuations on the domain wall dynamics in various regimes, including the low field/current creep regime studied here as well as the high driving force regime above the Walker breakdown. Of particular importance for practical applications is also the effect of thermal fluctuations in the case of zero applied fields/currents, which should limit the life time of the “magnetic bits” stored in nanoscale wires and strips.

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